

ATTENUATION STATISTICS DERIVED FROM EMISSION MEASUREMENTS
BY A NETWORK OF GROUND-BASED MICROWAVE RADIOMETERS

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Abstract--Two seasons (1987: December through 1988 February; and 1988: June through August) of thermal emission measurements, taken by a multi-channel, ground-based microwave radiometer, are used to derive single-station zenith attenuation statistics at 20.6 and 31.65 GHz. For the summer period, statistics are also derived for 52.85 GHz. In addition, data from two dual-channel radiometers, separated from Denver by baseline distances of 49 and 168 km, are used to derive two-station attenuation diversity statistics at 20.6 and 31.65 GHz. The multi-channel radiometer operated at Denver, Colorado; the dual-channel devices operated at Platteville and Flagler, Colorado. The diversity statistics are presented by cumulative distributions of maximum and minimum attenuation.

I. Introduction

With the deployment of communication satellites such as OLYMPUS, (Brussard, 1988) ITALSAT, (Paraboni, 1989) and ACTS, (Davarian, 1989) there is an increased need to know atmospheric attenuation at frequencies higher than 20 GHz. At these frequencies, attenuation is strongly influenced by water vapor, oxygen and clouds. Currently, there is a lack of information on cloud attenuation and its temporal and spatial variability. Although they are not widely available, dual-frequency microwave radiometers are unique in deriving integrated cloud liquid from attenuation measured during cloudy conditions. In this paper, radiometer data from three locations have been processed to derive both single- and two-station cumulative attenuation distributions. The data given here provide information both on frequency scaling and on-site diversity. Separation distances of 49 and 168 km are examined.

II. Instrumentation

Over the past decade, the Wave Propagation Laboratory (WPL) has designed, constructed, and field-tested several ground-based microwave radiometers to observe the atmosphere (Hogg, et al, 1983). These instruments were designed to run continuously, to provide unattended observations, and to operate in almost all weather conditions. A prototype six-channel radiometer, having channels at 20.6, 31.65, 52.85, 53.85, 55.45, and 58.8 GHz, operates at Stapleton International Airport in Denver, Colorado, USA. All channels point in the zenith direction from the same location and have equal beamwidths of 2.5°. After data processing,

the instrument provides 2-min-average measurements of temperature, precipitable water vapor, and integrated cloud liquid. The radiometer is about 10 m from a U.S. National Weather Service rawinsonde launch facility; hence, ground-truth meteorological data from balloon soundings of temperature, water vapor, and pressure are available twice daily. These radiometers are well known for their meteorological capability (Askne et al., 1986); they are also useful in radio communication studies (Westwater and Snider, 1989). In addition to the currently operating six-channel instrument in Denver (Den), from 1985 to 1988 WPL operated a network of three zenith-viewing dual-channel radiometers in the plains of eastern Colorado. Data from two of the stations, Platteville (Plt) and Flagler (Flg) are analyzed here. The Plt station is separated from Den by 49 km; the distance between Flg and Den is 168 km. Both stations differ in altitude from Den (1.612 km MSL) by less than 150 m. These radiometers operated at 20.6 and 31.65 GHz, and differed from the Denver radiometer by having 5.0° beamwidths. We have experimentally studied the effects of different beamwidths by operating a transportable radiometer that has a 2.5° beam along side each of the network radiometers. The correlation coefficients describing the data taken by the transportable and by the Plt and Flg radiometers were 0.99 and 0.90 (Snider, 1988). For the Den system, we do not derive attenuation from 53.85, 55.45, and 58.8 GHz channels because, even in the clear air, the ambient brightness temperatures from these channels are near saturation. These upper three channels were chosen to measure lower atmospheric temperature profiles.

The dual-channel radiometers are calibrated using the "tipping curve" method (Hogg et al., 1983); emission measurements as a function of elevation angle are required for this method. The 52.85-GHz channel is calibrated by comparing emission measurements with values calculated from radiosondes. Both methods of calibration require clear-sky conditions. The absolute accuracy of brightness temperature measurements is estimated to be about 1 kelvin (K). For an ambient signal level of 100 K, this accuracy is roughly equivalent to an attenuation error of 0.05 dB, or a relative accuracy of 2.4%. By using a well-known relationship derived from the radiative transfer equation, the radiometer output at each operating frequency is related to the atmospheric brightness temperature T_b and total absorption τ (in nepers) by (Westwater, 1978)

$$T_b = 2.75 e^{-\tau} + T_{mr}(1 - e^{-\tau}) \quad (1)$$

where T_{mr} is a mean radiating temperature of the atmosphere and 2.75 is the cosmic background brightness temperature (both in kelvins). We further approximate the profile-dependent variable T_{mr} by a constant that is calculated from climatological radiosonde data (Westwater, 1978). We solve (1) for τ and compute total absorption (in decibels) from measured T_b by

$$\tau(\text{dB}) = 4.34 \ln \frac{(T_{mr} - 2.75)}{(T_{mr} - T_b)} \quad (2)$$

Typical time series of three-frequency data from Den and two-frequency data from Plt are shown in Fig. 1. The sharp maxima in T_b 's are due to liquid-bearing clouds; note the different response to clouds for each observing frequency. Generally speaking, the liquid contribution to absorption (and hence to emission) increases as the square of the frequency. The water vapor response is more significant near the 22.235 GHz rotational spectral line. As inferred from the dual-channel radiometers, the precipitable water vapor for this day was about 2.0 cm at each station. However, the onset of continuous liquid-bearing clouds began in Plt at around 1100 UTC and at Den at around 1600 UTC. Isolated clouds occurred at both stations before these times.

III. Attenuation Statistic

Preliminary screening of data was done by visual inspection of 24-h time series. For example, outliers arising from occasional non-zenith observations were eliminated this way. Additional editing required scatter plots displaying the 20.6 and 31.65 GHz data. Outliers detected by this method included those arising from melting snow on antennas or from rain. Roughly, about 15% of the theoretical maximum number of data for both seasons were not available. This percentage also includes power outages and problems associated with communications. To derive joint-station statistics, we placed both the Plt and Flg data into one-on-one correspondence with Den, within a time uncertainty of ± 1 minute. Then, at each 2-min time interval, if both samples of data from station pairs passed editing, both were included in the statistics; otherwise, both were deleted.

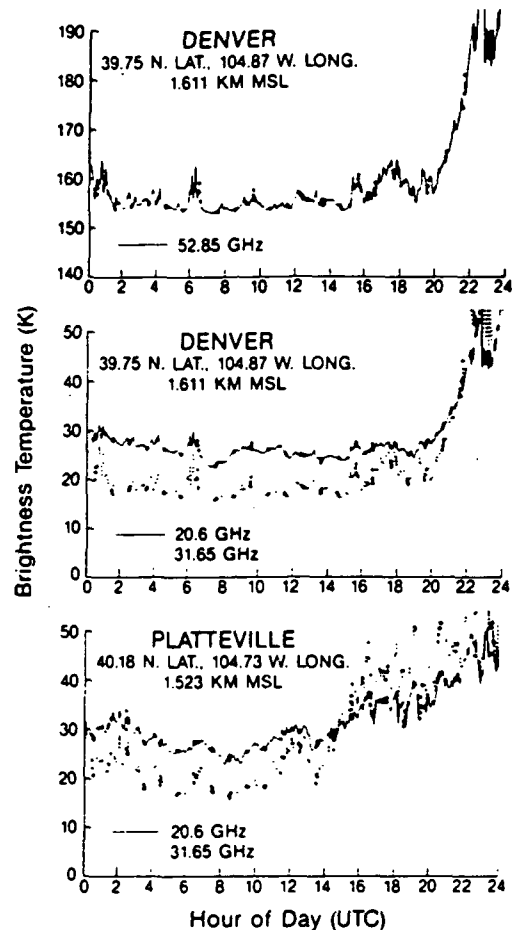


Fig. 1. Time series of zenith brightness temperatures at 20.6, 31.65, and 52.85 GHz. Denver and Platteville, Colorado. 13 September 1988.

A. Denver-Platteville Statistics

For the Den and Plt locations, we derived summer (July, August, and September) and winter (December, January, and February) statistics; the 52.85 GHz radiometer did not operate during the winter of 1987-1988. The single-station cumulative distributions

for Den and Plt are shown in Fig. 2. We note that, in the winter, 2.5 dB is exceeded less than 0.01% of the time. These low values of attenuation are due to the limited amount of cloud liquid water that cold winter clouds can contain. For summer conditions, the presence of greater amounts of precipitable water vapor, as well as of clouds with higher liquid content, gives rise to higher values of attenuation. At 31.65 GHz, for example, values of 5 dB are exceeded about 0.1% of the time. Note that only small differences occur between the statistics for the two locations. Also note the much higher attenuation at 52.85 GHz; this is caused both by the increased oxygen absorption and by the higher attenuation from water vapor and clouds. Based on Den data, a regression analysis using measured attenuations at 20.6 and 31.65 GHz to predict attenuation at 52.85 GHz gave a correlation coefficient of 0.957 and a residual rms prediction error of 0.21 dB.

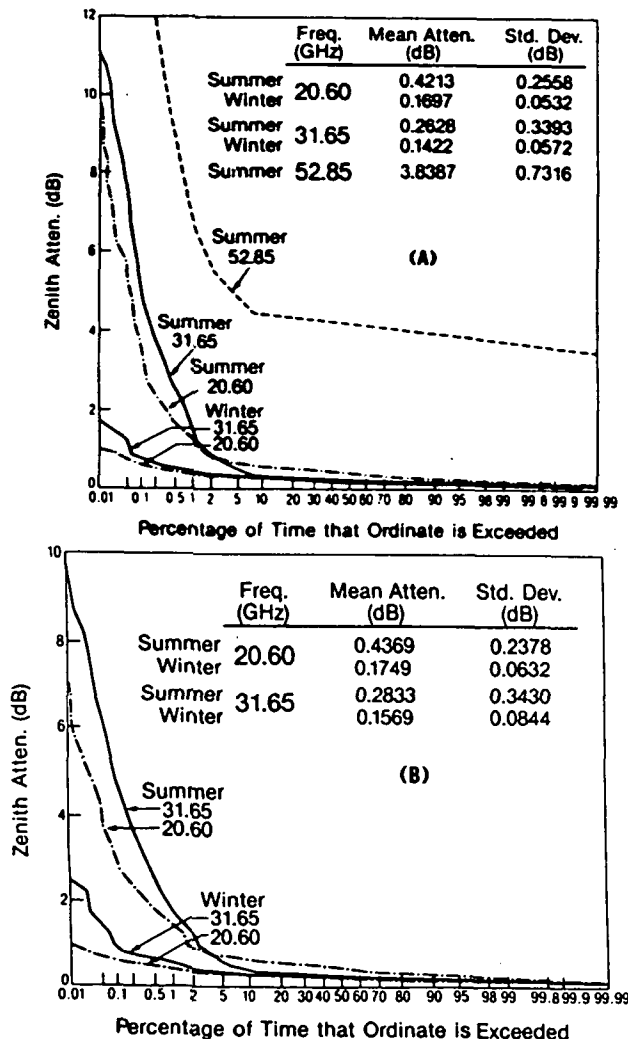


Fig. 2. Single station cumulative distributions of zenith attenuation for (A) Denver, Colorado, and (B) Platteville, Colorado. Sample size: summer-46539; winter-41298.

From these derived time series, we constructed cumulative distributions for the winter and summer seasons (Fig. 3). We note that, at the 0.01% level, only 1-2 dB is gained by the difference in maximum and minimum attenuation during winter conditions. However, in summer, when significant attenuation from clouds can occur, a margin of 8 dB is gained at 31.65 GHz.

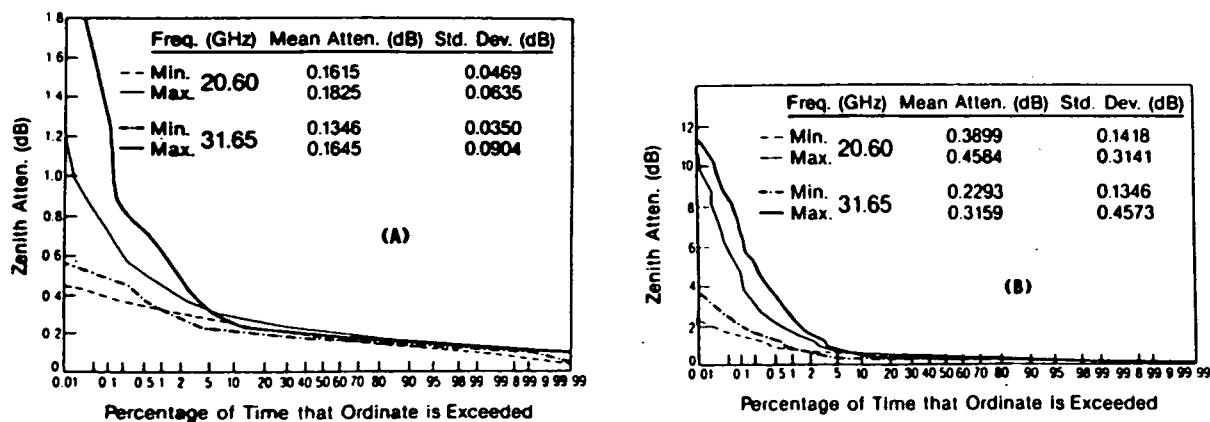


Fig. 3. Joint station cumulative distribution of maximum and minimum zenith attenuation measured at Denver and Platteville, Colorado. (A) Winter 1987/1988; (B) Summer 1988. Sample sizes given in the caption of Fig. 2.

We also determined the percentages of time that measurable cloud liquid ($L \geq 0.04$ mm) was present at Den, at Plt, or at both locations. These results, shown in Table 1, indicate that only slight differences exist between Den and Plt for either of the two seasons. Clouds exist at both stations simultaneously roughly about 6% of the time; conversely, this means that either one or both stations are clear about 94% of the time.

TABLE 1. Percentage of time that measured cloud liquid exceeded threshold of 0.04 mm.

Season	Single Station	$L \geq 0.04$ (mm)
Winter	Den	10.4 %
	Plt	12.2 %
Summer	Den	9.5 %
	Plt	10.6 %

Season	Clouds at both Stations $L \geq 0.04$ (mm)
Winter	5.8 %
Summer	6.0 %

B. Denver-Flagler Statistics

Because of the low values of observed attenuation during the winter ($\sim < 2$ dB), we only derived statistics for Den-Flg during the summer. The single station cumulative distributions at 20.6 and 31.65 GHz are shown in Fig. 4. Note that, because of different sample sizes for the summer period, the Den statistics differ somewhat from those shown in Fig. 2A. The different sample sizes arise because there is a difference in times at which valid data were obtainable at Den-Plt and at Den-Flg. We also show cumulative distributions for the minimum and maximum of the 2-station data in Fig. 5. These results again show a ~ 9 dB diversity gain at 31.65 GHz, and that minimum attenuations of the order of 1 dB are obtainable with diversity at this separation.

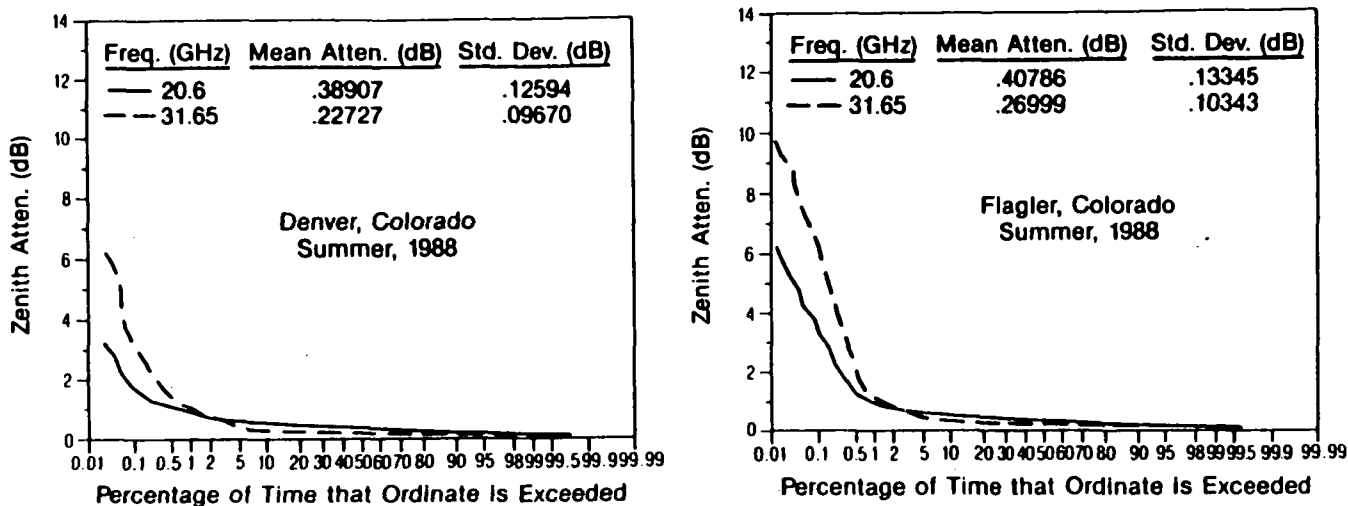


Fig. 4. Single station cumulative distributions of zenith attenuation for (A) Denver, Colorado and (B) Flagler, Colorado. Sample size-40283.

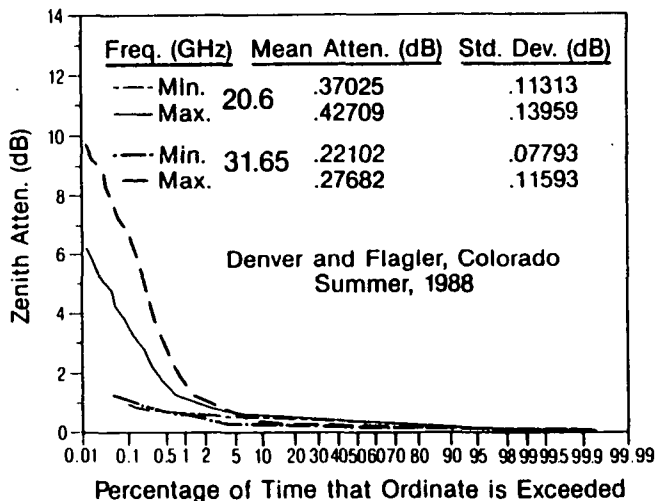


Fig. 5. Joint station cumulative distribution of maximum and minimum zenith attenuation measured at Denver and Flagler, Colorado. Sample size given in caption of Fig. 4.

IV. Summary

In summary, we used ground-based radiometer data to derive both single-station and two-station attenuation statistics for the attenuation range 0 to 12 dB. These statistics were derived at 20.6 and 31.65 GHz in Denver and Platteville, Colorado, for 3-month winter and summer seasons in 1988. In the winter, when integrated amounts of water vapor and clouds are low, attenuations were generally less than 2 dB. In the summer, attenuations of 10-12 dB were exceeded at the 0.01% level. For summer, as much as 8 dB was gained with site diversity (the two stations were 50 km apart). For summer data at stations separated by ~ 170 km again about 8 dB was gained by site diversity. For our data, as shown in Table 1, the effects of liquid bearing clouds could be reduced by about 50% by site diversity. Also, for the summer data at Denver, cumulative attenuation distributions at 52.85 GHz were also derived; 12 dB was exceeded at the 0.5% level. At the same percentage of time level,

0.5%, the attenuation at 31.65 GHz was 2.8 dB and at 20.6 GHz about 1.8 dB. The channel at 52.85 GHz would not ordinarily be chosen as a communication beacon because of the high background of oxygen attenuation; however, the data we present should be useful in estimating 50 GHz attenuation.

In general, radiometric data such as we have presented should be useful in determining the effects of clouds on next-generation communication systems that use frequencies above 20 GHz.

V. Status of Experimental Observations and Data Analysis

Attenuation data were recorded at several locations and frequencies (listed in Table 2) during 1989 and 1990. These data are currently being processed to derive clear and cloudy attenua-

Table 2. Radiometric Observations of Attenuation during 1989 and 1990.

<u>Location</u>	<u>Time Period</u>	<u>Frequencies (GHz)</u>	<u>Radiosonde Data</u>
Wallops Island, VA	4/11 - 5/8/89	20.6, 31.65, 90.0	Yes
Boulder, CO	9/5 - 10/4/89	20.6, 31.65, 90.0	No
Lacona, NY	12/15/89 - 2/28/90	20.6, 31.65, 90.0	Note 1
Elbert, CO	1/15 - 2/28/90	20.6, 31.65	Note 2

Note 1: Radiosonde observations were made only during storm periods.

Note 2: A limited number of radiosonde observations were made during clear weather; most soundings were obtained during storms.

tion statistics, frequency scaling of attenuation, and, where radiosonde data are available, to compare observed clear-air attenuation measurements with absorption calculated from models. Analysis of the Wallops Island data set is nearly complete. Comparisons of measured and calculated absorptions had to be repeated due to errors in the original radiosonde data supplied by NASA/Wallops. However, preliminary results from Wallops (Snider et al., 1989) are still valid.

The dual-channel radiometer employed at Elbert, CO, will be installed near Erie, CO, during June, 1990. Data from this system combined with data from Den and Plt will provide joint attenuation statistics for a new range of spacings as follows:

Erie - Platteville	27 km
Denver - Erie	41 km
Denver - Platteville	49 km.

It is planned to make measurements until approximately 1 December 1990 when the Erie system will be relocated to Elbert, CO, for additional aircraft icing measurements during early 1991.

The three-channel radiometer with steerable antenna will be moved to Virginia Polytechnic Institute and State University (VPI), Blacksburg, VA, in late summer of 1990. The radiometer will be operated for approximately 4 weeks to assist in the calibration of the VPI 20 and 30 GHz radiometers and beacon receivers observing the Olympus satellite. Individual and joint attenuation statistics will be calculated for the two data sets.

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